

# Study of kaonic final states in $\pi^- p$ at 190 GeV

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**Abstract.** We discuss the status of analyses of data recorded in the 2008 and 2009 runs of the COMPASS experiment at CERN with sepcific focus on final states with  $K_S^0 K_S^0 \pi^-$  and  $K^+ K^- \pi^-$  produced in  $\pi^- (190 \text{ GeV}) p$  scattering. The interest in such final states is motivated by a summary of some of the relevant literature. We also show first results from the analysis of diffractively produced  $K \bar{K} \pi$  states. Two prominent three-body structures, one around 1.8 GeV, the other at 2.2 GeV decaying via known  $K \bar{K}$  and  $K \pi$  states are seen.

**Keywords:** hadron spectroscopy; light meson spectrum; exotic mesons; gluonic excitations; open and hidden strangeness

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## INTRODUCTION

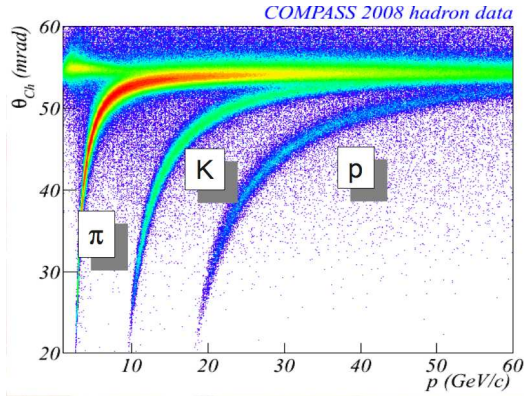
In light-meson spectroscopy final states including two kaons are interesting for several reasons. First, final state kaons mean higher thresholds, allowing cleaner spectroscopy of the heavier states. Second, no states with exotic quantum numbers have so far been observed in kaonic final states. Third, strange mesons are an interesting research topic by themselves. We shall outline our specific interests below.

The physics goals of the COMPASS [1] hadron runs are spectroscopy of mesons from central and diffractive production. Specific aims are the confirmation or rejection of hybrid or glueball states. The literature on both is vast. At the time of this writing, the SPIRES database finds 782 papers with “glueball” in their title. Out of these, 6 also have “evidence” in their title. But only two of these papers have been cited more than 5 times: one is a lattice calculation [2], the other [3] was followed by a paper by the same authors [4] phrasing their result as a question. Likewise a database search finds 200 papers on mesons with “hybrid” in their title. Yet, there’s not a single one whose title contains “evidence” or “confirm.” In other words, clarification and further experimental input are direly needed.

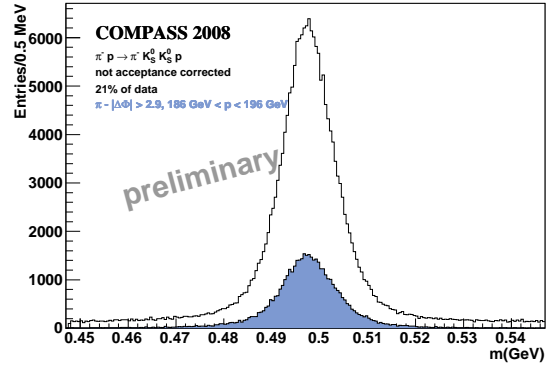
The COMPASS collaboration recorded diffractive scattering data on a liquid hydrogen target with both negative and positive hadron beams at 190 GeV during its 2008 and 2009 beam times. The forward-flying particles produced in the central or diffractive interaction were measured and identified by means of a two-stage spectrometer which features highly efficient track reconstruction from approximately 1 GeV upwards combined with particle identification in the wide-angle spectrometer and both electromagnetic and hadronic calorimetry in both stages of the spectrometer. Together, these components yield nearly  $4\pi$  coverage of the neutral and charged particles of the forward flying system. Further, in order to identify events where the target proton remained intact, a recoil proton detector was used which detected the slow proton emitted at large angles. At the same time a veto system ensured the absence of other slow particles between the recoil proton detector and the spectrometer acceptance, thought mostly due to inelastic excitations of the target.

In the COMPASS experiment kaons can be identified in essentially the following ways without recourse to physical processes:

- charged kaons can be recognized by means of a RICH detector, which measures the angle of Cherenkov radiation emitted by particles passing through its gas ( $\text{C}_4\text{F}_{10}$ ) volume. This angle is a function of the velocity  $\beta$  of the particles. Since track reconstruction in magnetic spectrometers measures the momentum  $p$  of the particles, their mass  $m$  can be recovered via  $p/m = \beta/(1 - \beta^2)^{1/2}$ . In our current analysis we use this to identify charged kaons between 10 GeV and 30 GeV. Figure 1a serves to illustrate the performance of the RICH detector.
- short-lived neutral kaons identify themselves through their displaced decay  $V_0$  vertex which gives the right mass if a pion hypothesis is made for its outgoing oppositely charged particles. Given the known [5] mean lifetime  $\tau = 0.9 \times 10^{-10} \text{ s}$  and the neutral kaon mass  $m(K_S^0) = 497 \text{ MeV}$ , this displacement can take



(a) Cherenkov angle versus particle momentum. Three bands appear. These correspond to different mass particles, from left to right: pions, kaons and (anti-)protons. The peak in the upper left corner is due to  $\delta$ -electrons.



(b) Distribution of reconstructed  $K_S^0$  masses before and after (filled histogram) exclusivity cuts (explained further down in text).

FIGURE 1. Kaon identification

TABLE 1. Predicted branching of  $\pi(1800)$  for different model assumptions [12]. Note the much suppressed  $K^*K$  branching for a strictly hybrid  $\pi(1800)$  compared to the case of a radial excitation.

	$\rho\pi$	$\rho\omega$	$\rho(1465)\pi$	$f_0(1300)\pi$	$f_2\pi$	$K^*K$	Total
$\pi_{3S}(1800)$	30	74	56	6	29	36	231
$\pi_H(1800)$	30	0	30	170	6	5	$\approx 240$

the order of a few meters at COMPASS energies. The most important background to the  $K_S^0$ s are  $\Lambda \rightarrow p\pi$  decays. Their contribution was verified to be negligible. Reconstructed  $K_S^0$ -masses are shown in fig. 1b. Note that the exclusive sample used in the analysis has very little background.

- finally, the beam carries a fraction of kaons ( $O(5\%)$ ). These are excluded by means of specifically designed Cherenkov detectors [6] which were placed in the beamline.

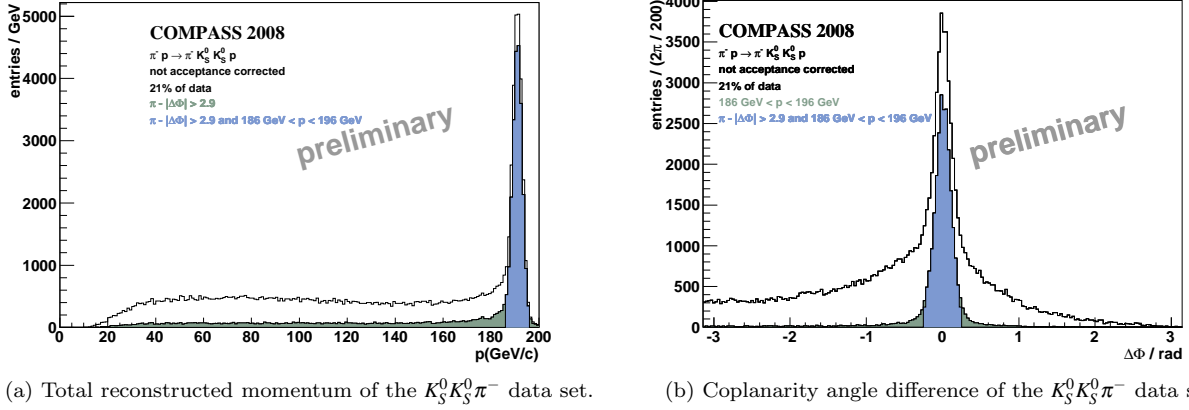
In this paper we discuss the current state of our analyses of the exclusive  $K^+K^-\pi^-$  and  $K_S^0K_S^0\pi^-$  systems produced in diffractive scattering of a  $\pi^-$  on a proton. The centrally produced  $K\bar{K}$  subsystem in the same channel was discussed previously [7, 8] where we also discussed the different quantum numbers accessible to  $K^+K^-$  and  $K_S^0K_S^0$ .

## PHYSICS EXPECTATION

The  $K\bar{K}\pi$  system, as produced in  $\pi^-p$  collisions, can exist with exotic quantum numbers  $1^{-+}$ . Preferential  $K^*(\rightarrow K\pi)K$  decay is expected from models of quartet and hybrid states [9, 10]. So far no kaonic exotics emerged from various experimentally studied production processes [11]. Since their existence is inevitable in flavor multiplet schemes, they can be considered touchstones of quartet models. COMPASS produced  $K\bar{K}\pi^-$  with high statistics, well suited for partial wave analysis. In addition to exotics, states or dublets with  $q\bar{q}$  quantum numbers like the enigmatic  $E/\iota(1405)$  or  $\pi(1800)$  will possibly make an appearance in these data.

The question whether the  $\pi(1800)$  is a radial excitation of the pion or a hybrid state or a combination of both, perhaps even two different nearby states, has been raised. Theoretical calculations of branching ratios in the different scenarios [12], quoted in table 1, have provided a reference frame for experiments to distinguish between the various possibilities. Results in this direction were given by VES [13] and E852 [14].

There are several contested states around 2.1 GeV that are left out of the PDG summary tables. One of special interest to us is the  $f_2(2150)$  which was found to decay to  $a_2(1320)\pi$  by the Crystal Barrel



**FIGURE 2.** Exclusivity of the  $K_S^0 K_S^0 \pi^-$  data sample. After the topological selection, two further cuts were applied: momentum within 5 GeV of the nominal 191 GeV and a coplanarity angle  $\Delta\Phi$  (defined in text) such that  $\pi - |\Delta\Phi| > 2.9$ . Both plots show the total sample, and the effect of each exclusivity cut on the other variable. The final set with both cuts is also indicated.

collaboration [15]. Following the systematization given in [16, 17] the  $f_2(2150)$  should be an  $s\bar{s}$  state and a radial excitation of the  $f_2(1525)$  which decays predominantly to  $K\bar{K}$ . Therefore, we expect the  $f_2(2150)$  to also decay via  $K^*\bar{K}$  and  $\bar{K}^*K$ .

## DATA SELECTION

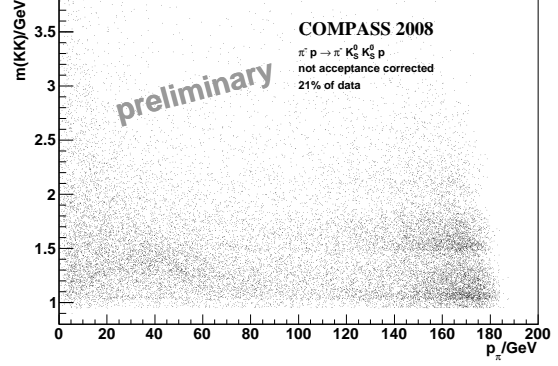
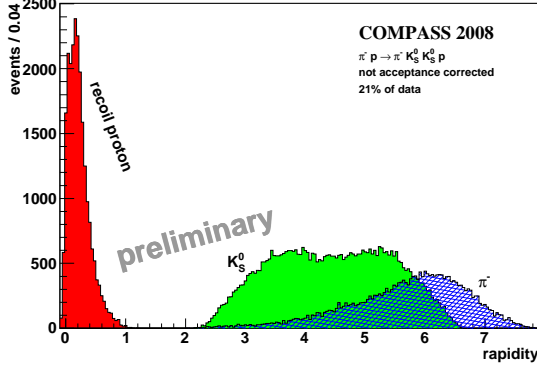
The data shown was selected from two weeks of the COMPASS 2008 hadron run. Details on the selection can be found in [7, 8]. The quality of the reconstruction and selection is illustrated with the exclusivity plots from the neutral kaon data, shown in fig. 2. One sees that momentum conservation by itself ensures a very clean selection owing to the purity of the COMPASS trigger system and the efficient track reconstruction. The coplanarity angle referenced is defined as the angle between the plane spanned by the beam direction and the momentum vector of the  $K\bar{K}\pi$  system on the one hand, and the plane spanned by the beam direction and the recoiling proton on the other. These planes should coincide by momentum conservation. Due to the segmented architecture of the recoil proton detector a precision of  $\approx 0.15$  rad is expected. This expectation is nicely matched by the data.

For the partial wave analysis, we kinematically fitted the  $K_S^0$  vertices to a mass hypothesis and included the so-obtained neutral tracks into the fit of the primary vertex in a way similar to the techniques given in [18, 19]. The plots shown are without these fits but the conclusions are not affected.

One remark concerns the use of the RICH detector in the charged kaon set. For the time being, we imposed a cut at 30 GeV above which we found that kaon identification became unreliable. This infers a significant cut in low 3-body masses where momentum conservation dictates that all final state particles have momenta well above 30 GeV. Imposing the same cut on the  $K_S^0$  data makes most differences between the pictures shown below disappear.

## STATUS OF ANALYSIS

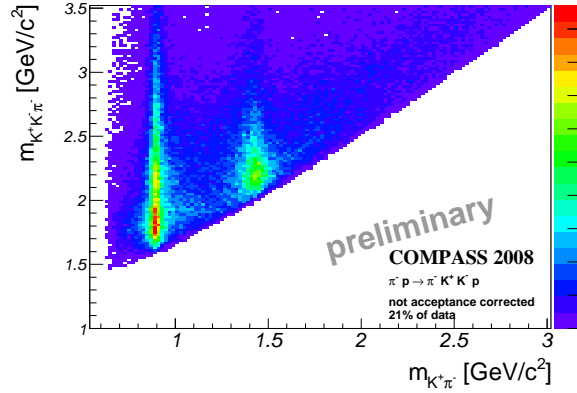
The presence of different production regimes is apparent in the neutral kaon data. Figure 3 illustrates this in two ways. The distribution of rapidities (fig. 3a) shows large overlap between the pion and kaon rapidities, but also a significant fraction where the pion rapidity exceeds that of the kaons. Diffractive production is characterized by the absence of a rapidity gap between the decay products of the diffractively excited resonance. For the partial wave analysis we selected a subset without an apparent rapidity gap. The division



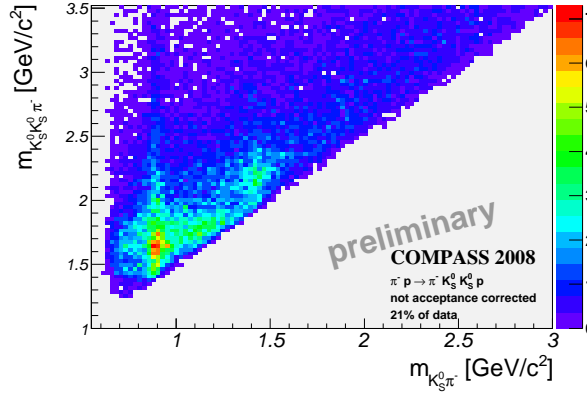
(a) Rapidity distribution of the  $K_S^0 K_S^0 \pi^-$ . There are two  $K_S^0$  entries per event.

(b)  $K_S^0 K_S^0$  mass distribution as function of the  $\pi$  momentum. Note the division into different production regimes.

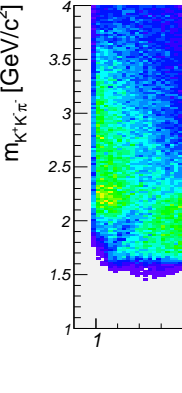
**FIGURE 3.** Illustration of different production regimes in the case of the neutral kaon data. (Not acceptance corrected.)



(a)  $m(K^+ K^-)$  against  $m(K^+ \pi^-)$



(b)  $m(K_S^0 K_S^0 \pi^-)$  against  $m(K_S^0 \pi^-)$  (two entries per event)



(c)  $m(K^+ K^-)$  against  $m(K^+ \pi^-)$

**FIGURE 4.** Two-body invariant masses against three-body invariant masses for the various possible combinations. All plots show three-body states around 1.8 GeV and 2.1 GeV selectively decaying through the various visible two-body states. Comparing figs. (a) and (b) shows the dramatic loss in the lower left corner of (a) due to the loss of high-momentum kaons explained in the text. (Not acceptance corrected.)

into different production processes is corroborated by fig. 3b which shows the  $K\bar{K}$  mass distribution over the momentum of the pion. For high pion momenta, the  $K\bar{K}$  mass spectrum develops detailed structure whereas for lower pion momenta the  $K\bar{K}$  mass spectrum appears to be dominated by the available phase space.

Figure 4 gives a detailed view of the mass spectra in the overall sample and how they relate. The first striking feature concerns the  $K\pi$  spectra (top row). There are very strong bands corresponding to the  $K^*(892)$  and the excited kaons (which we shall indiscriminately refer to as  $K(1430)$  in what follows) around 1430 MeV. There are two predominant structures in terms of the three-body mass: one at approximately 1800 MeV, one around 2.2 GeV. The lower two plots, which allow the same kind of quantitative analysis for  $K\bar{K}$  intermediate states, show two strong diagonal bands which are reflections of the  $K^*(892)$  and  $K(1430)$ . Besides these, one sees the  $f(980)$  /  $a(980)$  near the threshold and a well defined band near  $m(K\bar{K}) = 1500$  MeV which probably corresponds to the  $f_2(1525)$ . Again the clustering near  $m(K\bar{K}\pi) = 1800$  MeV and  $= 2.2$  GeV is apparent. The difference in structure between the charged and the neutral case is significantly reduced if one reproduces

the low-momentum cut needed for the charged kaons in the neutral case.

A preliminary partial wave analysis of the structure near 1800 MeV was done. The resulting partial waves turned out to be compatible with a significant  $\pi(1800)$  contribution. The structure at 2.2 GeV appears consistent with spin 2. No further or definite conclusion can be drawn at our current state of PWA.

## OUTLOOK

We have shown promising results from our preliminary analyses of diffractively produced  $K\bar{K}\pi^-$  states. Refining our selection and incorporating the complete data set of the 2008 and 2009 COMPASS runs will put us in a position which will allow partial wave analyses encompassing large parts of the known and unknown light meson spectrum. We have shown that our partial wave software is in a state that allows first preliminary conclusions but a significant amount of work remains to be done, both in understanding our acceptance and in implementing the various intermediate states. Yet, the future looks bright.

## ACKNOWLEDGMENTS

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